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Photographic investigation of air shock phenomena from decigram charges

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PHOTOGRAPHIC INVESTIGATION OF AIR SHOCK PHENOMENA FROM DECIGRAM CHARGES

PATRICK W. WILSON
AND
CHARLES J. TREAT

PHOTOGRAPHIC INVESTIGATION

OF

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Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
PHYSICS

United States Naval Postgraduate School
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ABSTRACT

An ultra high speed photographic method was developed for the laboratory investigation of shock wave phenomena from decigram charges. An electronic flashtube with three microsecond duration at one-third peak illumination was used as light source.

Arrival time data from 0.3 gram center-detonated spherical charges of P.E.T.N. was obtained and used to calculate overpressures which are compared to theoretical and experimental data from other sources. Agreement between these experimental results and the results calculated from thermodynamic theory are excellent for the primary shock but a substantial deviation is observed in the second shock data which may indicate that thermodynamic theory is incomplete for this phenomenon.

The excellent photographs of primary, secondary, and reflected shocks and the correlation of results obtained therefrom indicate that the method is useful for the study of explosive shock phenomena and may be used to obtain much of the information heretofore gained from extensive field test.

ACKNOWLEDGMENT

The assistance and encouragement of Professors A. R. Frey, G. F. Kinney, L. E. Kinsler, J. F. Sinclair, G. H. McFarlin, and W. C. Smith are gratefully acknowledged.

Further, the technical support and assistance of the Postgraduate School Machine Shop, Photographic Laboratory, and the technicians of the Engineering School Physics Department were invaluable in the successful completion of this project.

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TABLE OF SYMBOLS AND ABBREVIATIONS

a - (cm/sec)	=	Speed of sound under prevailing ambient conditions
ΔA - (ergs)	=	Calculated energy of explosion
ΔE - (Kcal/gm mole)	=	Calculated Heat of Explosion
M - (dimensionless)	=	Mach Number
P_o - (dyne/cm^2)	=	Atmospheric pressure in undisturbed air under prevailing ambient conditions
ΔP - (atmospheres)	=	Overpressure ($\frac{P}{P_o}$ - 1) where P is Peak total pressure
R_o - (cm)	=	Observed radius of outer shock
R_i - (cm)	=	Observed radius of inner shock
ΔS - (cal/gm mole ^oK)	=	Calculated entropy of Explosion (includes "Entropy of Mixing")
T - (^oK)	=	Temperature (absolute) of prevailing ambient conditions
t - (μ sec)	=	Delay Time or Arrival Time of shock wave at an observed Radius R
t_a - (μ sec)	=	Arrival time of sound wave at an observed Radius R under prevailing ambient conditions
W - (gms)	=	Charge weight
α - (cm)	=	Reduced energy parameter = $(\Delta A/P_o)^{\frac{1}{3}}$
γ - (dimensionless)	=	Specific heat ratio C_p/C_v taken as 1.403 for air at prevailing ambient conditions
λ - (dimensionless	=	Reduced radius parameter = R/α
ρ - (gm/cm^3)	=	Density of air under prevailing ambient conditions
τ - (dimensionless)	=	Reduced time parameter = t_a/α

1. Introduction

Usually the method employed in studying shock wave phenomena from air burst charges involves the performance of experiments using relatively large charges and a system of pressure gages at measured points in the path of the shock wave. This experiment was undertaken to determine the feasibility of employing a method of explosive shock wave photography as developed by Dr. H. E. Edgerton (Reference 5) to obtain time-distance data. This method is of value if these time-distance data from small charges may be shown to correlate with overpressure data from field experiments conducted with larger charges. A discussion of the reduction of the experimental results to dimensionless parameters which permit direct comparison of different quantities and types of explosive is presented in this report.

2. Experimental Setup

The physical layout of apparatus used to conduct this investigation is shown in Figures (1), (2), and (3).

Small spherical charges were suspended beneath a blast table by the wires used to detonate the charge. Closing the firing circuit causes the charge to detonate. Light from the detonating charge actuates the photocell causing it to send a pulse to the electronic delay circuit. A nondelayed pulse generated by this delay circuit is sent to the oscilloscope to start the timing sweep. A second pulse, delayed by a variable number of microseconds is sent to the oscilloscope to provide a mark on the timing sweep and simultaneously to the high voltage source of the electronic flash tube. The light from the flash tube forms a shadow of the shock wave on the reflective screen where it is photographed by the camera.

The blast table consisted of an aluminum plate 5/16 by 8 by 52 inches long. This plate was drilled and tapped at the center and six inches from one end to accept a brass charge support rod. Holes were also provided near the brass support rod for detonator wire access. A shield was mounted on each side with a 1/8 inch insulating air space provided between blast table and each shield to facilitate heating of the center plate. This assembly is mounted on four support rods in such a manner that the height may be adjusted to any desired level. The support brackets were attached to the laboratory bench by two "C" clamps. This blast table was designed to provide a shallow thermal layer on the underside when heated from above. For this reason charges were fired beneath the table. The underside of the blast table and side shields were painted flat black to minimize light reflection and resulting photographic difficulties.

The photographic light source used on this experiment consisted of an Edgerton, Germhausen, and Grier Fx-11 Xenon filled electronic flash tube, and its associated electronic circuitry. This flash tube consists of a Vycor tube surrounding electrodes spaced 1/8 inch apart. The filling gas is under 152 cm Hg pressure. The tube specifications rate this tube at one candlepower with 1/3 peak duration of three microseconds. Minimum voltage requirements are specified as 1200 volts with 600 volts starting potential. Assistance in the design of circuitry to provide these voltages was obtained from Professor W. C. Smith of the Electrical Engineering Department. A transformer acting through a beam power tube acting as a rectifier charges a 1.75 microfarad capacitor to 1200 D.C. volts which are applied to the electrodes of the electronic flash tube. A capacitance of 2.2 microfarads charged to 385 volts is applied across a thyratron switch. Upon firing of the thyratron by the pulse from the electronic delay circuit this voltage is discharged through a six volt spark coil to provide starting voltage at the center of the electronic flash tube. An auxiliary circuit and toggle switch provide for test firing of the light. Two standard fuse clips secure the tube to a mounting board which is positioned so that the light is beneath but shielded from the camera lens. A point light source is provided by enclosing the tube in a cylindrical container with a small aperture. The inside of the container is lined with a reflective surface to increase intensity.

A JRC-927 photoelectric tube with one stage of amplification, utilizing an external power supply, was used to initiate the timing sequence by receiving light from the detonating charge and sending a pulse to the electronic delay circuits.

Electronic delay up to 600 microseconds was provided by two TS-419/U radar test sets used as delay units, each of which contain a variable delay of 0-300 microseconds. The pulse from the photocell amplifier causes the first delay unit to send an undelayed pulse to the timing oscilloscope where it is used to trigger the timing sweep. The delayed pulse after passing through both delay units is used to fire the electronic flash tube and to provide a timing mark on the oscilloscope sweep. These TS-419/U were utilized to provide the required delay after other methods including multivibrator and radar range generators had proven unsatisfactory.

To calibrate the timing sequence the following procedure was used. Since there was an unknown delay factor in the photoelectric cell, it was necessary to calibrate in such a manner as to determine this delay throughout the entire range of delay. This was accomplished by first determining the total delay of the photocell and the two delay units, and then determining the delay of the two delay units alone. To obtain the first a General Radio Strobotac (Fig. 2) was utilized to provide a light to the photocell and simultaneously initiate the timing sweep from the Strobolux trigger outlet. This provides a simultaneous light source and trigger pulse. The light acting on the photoelectric tube provides a pulse which is delayed through the two delay units and displayed upon the oscilloscope as a mark on the timing sweep. The calibrated markings of the 315A Tektronix oscilloscope were used to accurately measure this total delay for various settings throughout the range covered by the delay units. To obtain the second, the undelayed output of the first delay unit was utilized to trigger the timing sweep as would be done in a normal firing sequence. Again the 315A oscilloscope was used

to accurately measure the delay for the same series of settings as in obtaining the total delay. A graph was prepared plotting results of above procedures as ordinate and abscissa. For any delay measured on the oscilloscope trace, the total delay may be read from this calibration curve. (See Appendix I.)

A 4 x 5 Press-type camera was used in this experiment with ASA 50 Penchromatic film producing the best results.

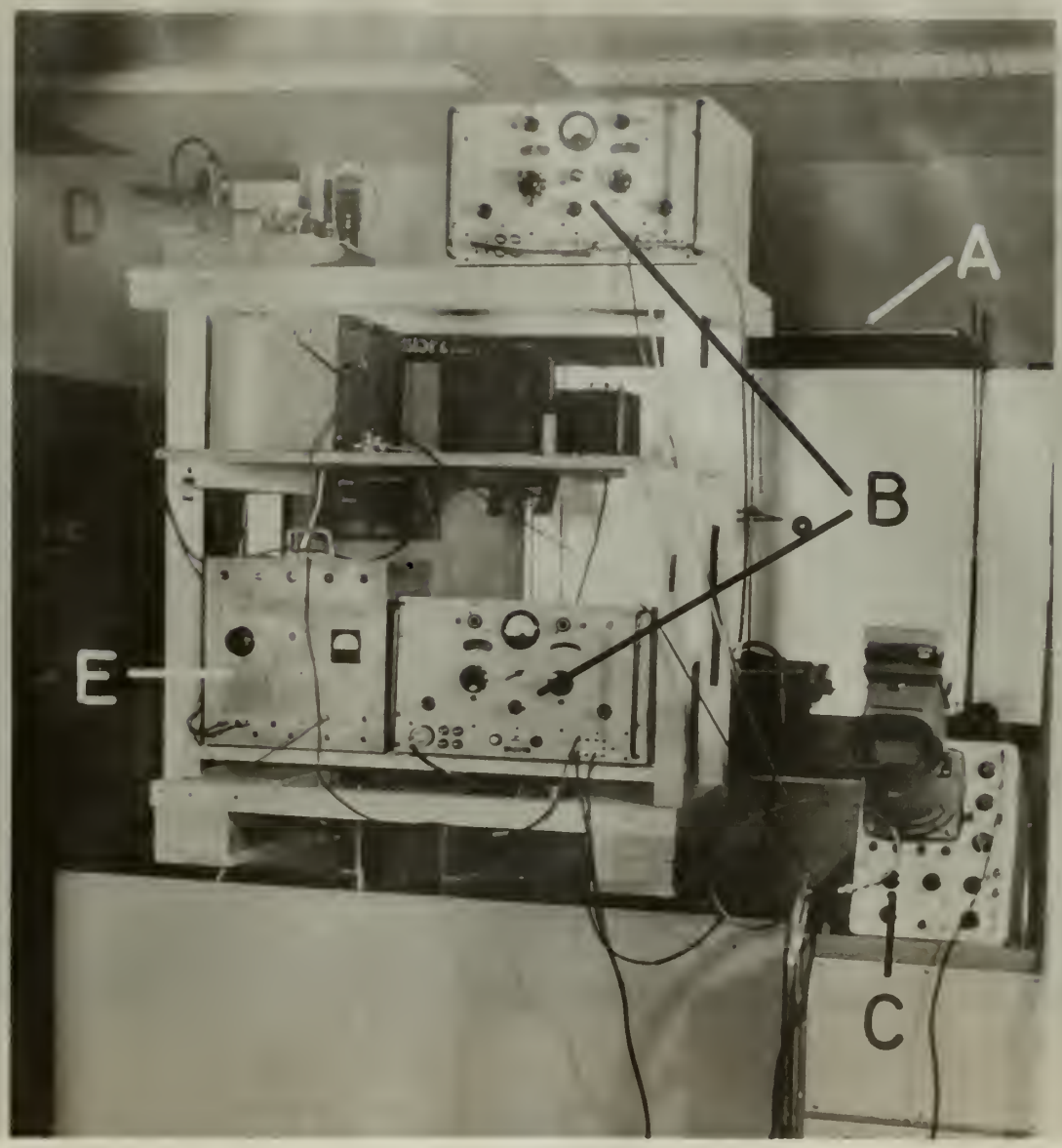


Fig. 1

A - Blast Table
B - Electronic Delay
C - Oscilloscope
D - High Voltage Source
E - Power Supply

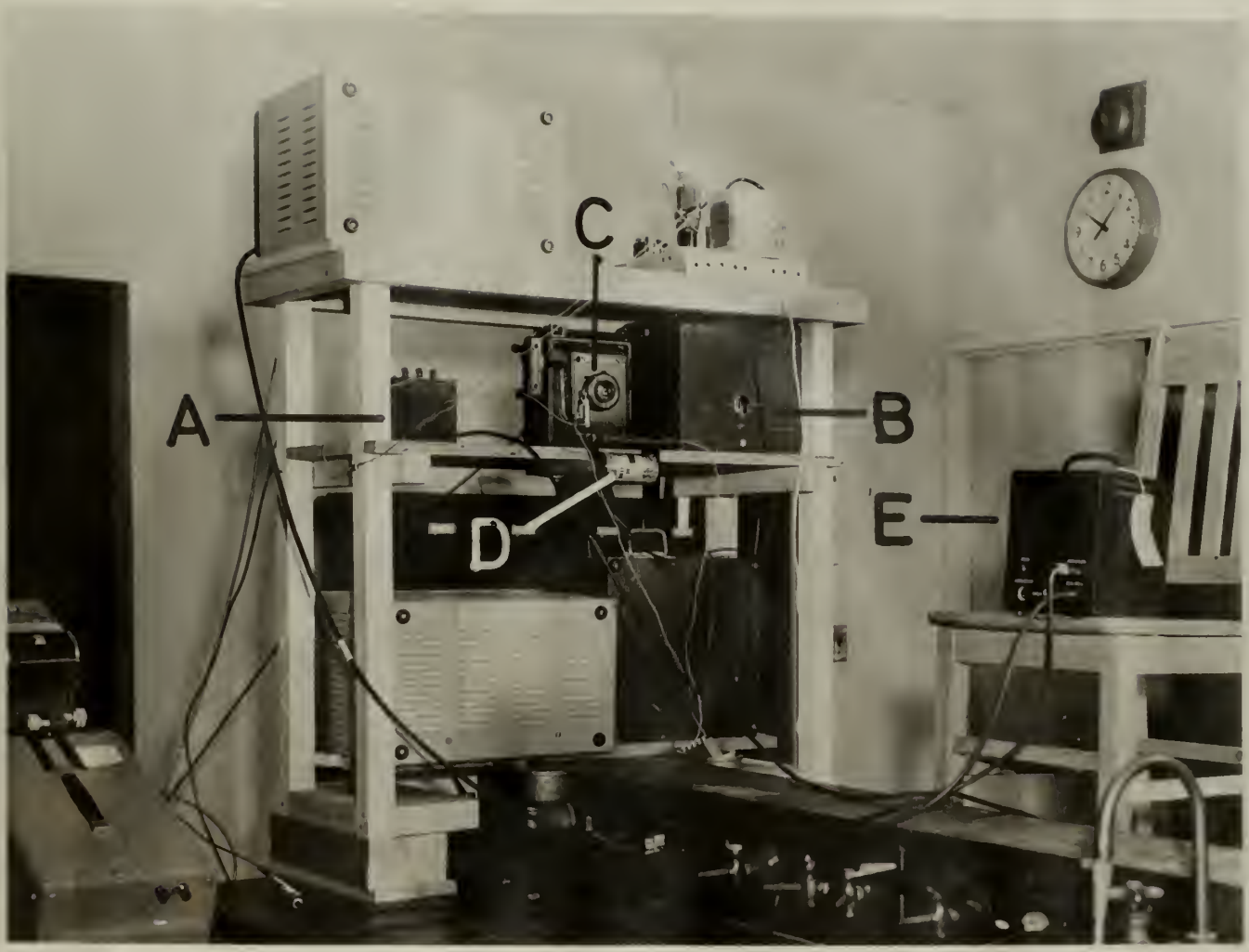


Fig. 2

A - Firing Box
B - Photo-cell
C - Camera
D - Light Source
E - Strobotac

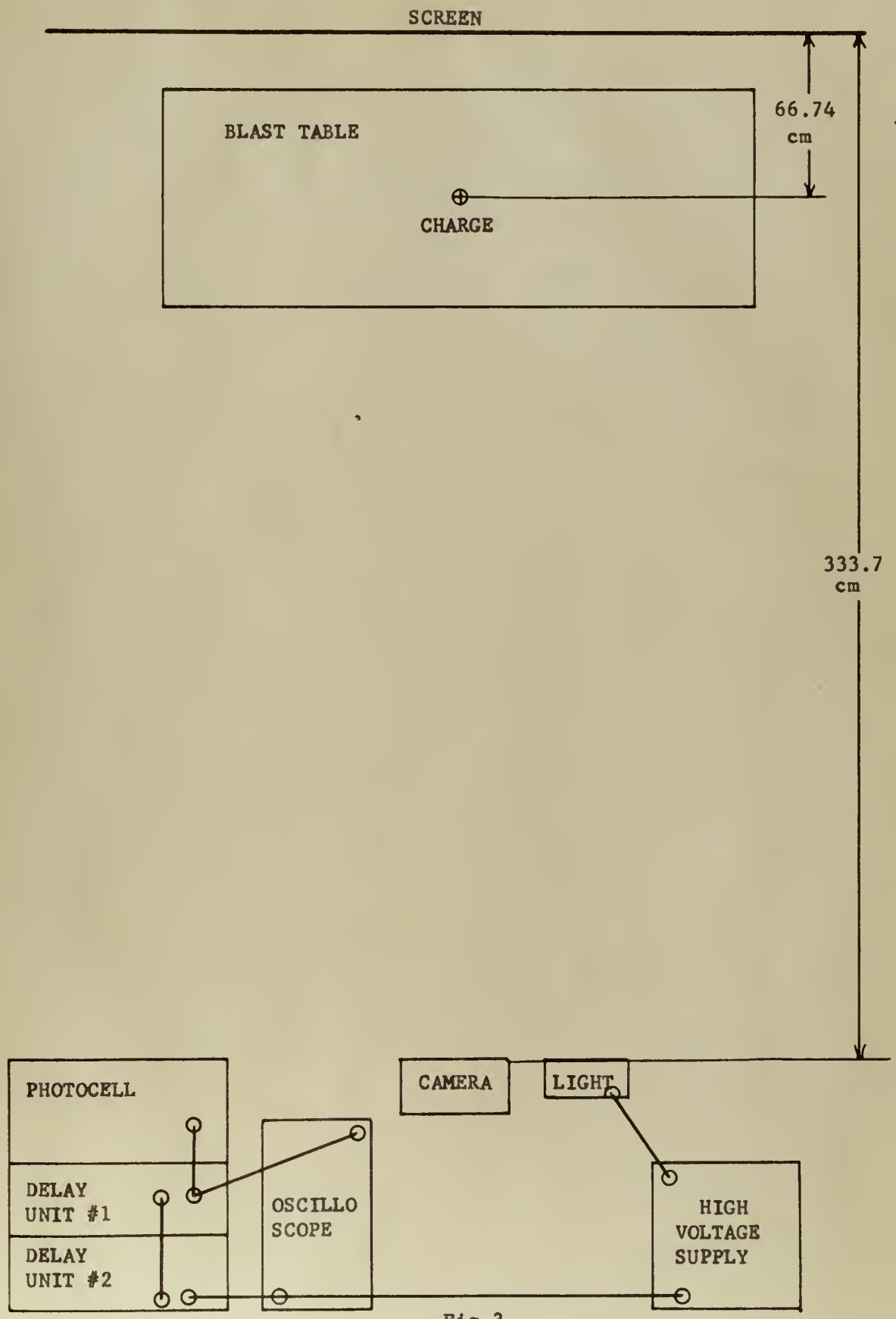

SCREEN
BLAST TABLE
66.74
cm
CHARGE
333.7
cm
PHOTOCELL
DELAY
UNIT #1
DELAY
UNIT #2
OSCILLO
SCOPE
CAMERA
LIGHT
HIGH
VOLTAGE
SUPPLY

Fig 3

3. Preparation of Spherical Charges

In this study it was desired to produce as nearly a spherical shock front as possible. The method used for large charges is to cast segments which are joined together around a centrally located detonator. Here we desired a very small spherical charge also detonated from the center. Briefly, the method used was to prepare small detonators of lead styphnate and lead azide directly on short lengths of ni-chrome wire. The spherical charge of P.E.T.N. was then pressed around the detonator. P.E.T.N.(Penta-Erythritol Tetranitrate) was chosen as the primary explosive for two reasons. First, it is rather sensitive, which reduced the problem of initiation. It can be detonated directly by the explosion of a bridge wire under proper conditions. The second reason for choosing P.E.T.N. was availability and reproducibility. Good quality material was produced without significant difficulty in the Organic Chemistry Laboratory.

While P.E.T.N. is commercially available, for the amount required in this experiment it was considered more feasible to prepare the material in the chemistry laboratory in sufficient quantity only to meet the immediate need.

The following method of preparation, taken from Davis, T., Chemistry of Explosives, was found to give satisfactory yields.

"Add a little Urea to 40 milliliters of fuming nitric acid: warm and flow dry air through until the nitric acid is completely decolorized. Cool in a 125 milliliter beaker in a freezing mixture of ice and salt. Add 10 grams of Penta-erythritol a little at a time with constant stirring, keeping the temperature below 5^{o} C. Stir and cool for an additional 15 minutes, then pour into 300 milliliters of cracked ice and water.

Filter this crude product, wash free from acid, using distilled water, and digest for 30 minutes with 100 milliliters of .5% Na_2CO_3 solution. Filter, wash, dry, and recrystallize from acetone. Melting point 140-141° C. Short, prismatic needles, insoluble in water, difficultly soluble in alcohol and ether."

For the purposes of this experiment all amounts in the above directions were doubled giving a yield somewhat in excess of 10 grams of P.E.T.N. of good quality.

The grinding of crystalline P.E.T.N. was found to present no problems, provided the P.E.T.N. was properly dried. An electrically operated grinder, manufactured by Fisher Scientific Co., was utilized, although the material could be hand-ground with mortar and pestle if necessary, provided gloves and face shield were worn and ordinary explosive safety precautions observed. The material was ground in lots of approximately one (1) gram each. Each lot of material was ground until no crystals nor lumps were visible and the material appeared to have the texture of flour.

After grinding, the P.E.T.N. was placed in weighing bottles and the bottles, with tops off, were stored in properly marked dessicators containing active dessicant. This type storage is necessary since in the powder form the P.E.T.N. appears to be hygroscopic.

The detonators used to initiate the charges fired in this experiment consisted of a high resistance wire, a small amount of heat sensitive lead styphnate and a small amount of shock sensitive lead azide. The preparation of these detonators, while not difficult, is principally a matter of experience. Several alternate methods of initiation were tried before one was selected for use.

Materials used in preparation of detonators consisted of Lead Styphnate, Lead Azide, small aluminum receptacles, a camel's hair brush, "Duco" china cement, Ni-chrome wire such as is standard for use in oxygen bomb calorimetry, acetone, a chemistry laboratory stand, an adjustable clamp to mount on the stand, and two small sticks of wood. Each of these is shown in the Figure 4 and will be identified in the text by its appropriate symbol. The aluminum cups, Ni-chrome wire, laboratory stand and adjustable clamp are of course, not critical and undoubtedly better materials and methods could be devised. These were used because of ready availability.

A small notch was filed in each arm of the laboratory clamp (A) and the clamp was adjusted so that a small amount of tension is exerted on the wire when it is in place. To hold the wire two match sticks (B) were split for about 1/4 inch. The wire is inserted in this split with about 1/4 inch of wire extending beyond each stick and then one complete turn about each stick is made with the free end of the wire. Prior to insertion of the wire in the clamp it was found to be advantageous to make a very small loop in the center of the wire to facilitate beading of the lead styphnate. A fairly good tension must be exerted in making this loop since any "give" in this loop during the handling and pulling necessary in charge preparation resulted in a cracked or broken detonator and probable failure of the charge. Figure 4 also shows a prepared wire on which, for illustration, one of the ends has not been wrapped around its stick (B). This photograph also shows a completed wire in place in the clamp. The length of wire used is immaterial needing to be only long enough to provide easy handling and a good fit in the dies used to press the charges. In this experiment it was found most convenient to

use a length equal to the length of the paper spool on which the wire was received (C).

The lead styphnate and lead azide used are similarly treated so will be discussed together. In one of the small aluminum cups (D) is placed approximately 0.3 to 0.5 grams of lead styphnate. The cup is tilted and tapped lightly to move the material to the low side. The cup may be propped in this position by placing a folded paper or small wooden block under the edge of the cup away from the material. Using a small squeeze bottle filled with acetone (E) the cup is washed from the high to the low side until all material is completely immersed in acetone. Two drops of "Duco" china cement are drained from the tube and allowed to fall directly on top of the lead styphnate. The amount is not critical although an excessive amount of cement made the operation more difficult and resulted in a lower percentage of initiation. Using a very small, No. 1, camel's hair brush from which about half of the bristles have been removed and with the end of the brush cut off square, the cement and lead styphnate are thoroughly mixed. The final consistency to be desired is a matter for individual experimentation. The consistency settled on during this experiment was a very thin paste when completely immersed in acetone. This permitted easy cleaning of the brush in the acetone covering the mixture and still gave rapid drying in air and a reasonably good strength when dry. The china cement, when used in reasonable amounts, appeared to cause no initiation difficulties. The lead azide is prepared in exactly the same manner. The same brush is used for both mixtures being rinsed in the acetone covering the mixture and wiped clean prior to inserting in the other mixture.

With the wire placed in the clamp the actual "Buttering" operation

is a two-step process. A small amount of the lead styphnate-cement mixture is scooped up on the bristles of the brush, allowed to dry momentarily in the air to increase its viscosity, and carefully deposited on the loop formed in the center of the wire. Ideally, the deposited bead should be about one millimeter in diameter, centered about the wire and surrounding the loop.

With the lead styphnate bead in place on the wire it is allowed to dry while the brush was cleaned as described above. Figure 4(F) shows a prepared wire with the lead styphnate bead applied.

The second step of the process is to coat the lead styphnate bead with the previously prepared lead azide-cement mixture. The application is done in precisely the same manner as used with lead styphnate. Small amounts of material are scooped up on the bristles of the brush, dried momentarily in air, and deposited by a very light brush stroke on the lead styphnate bead. If too much acetone is deposited with the explosive, the entire bead softens and falls from the wire. Great care was taken to cover the lead styphnate surface completely with lead azide. The completed detonator consisted of the wire with a pale yellow bead of approximately 2-3 millimeters diameter located near its center. Any reddish discoloration of the bead is cause for rejection since this color is caused by a mixing of lead styphnate with the lead azide and appearing on the surface of a well-centered and fully-coated bead indicates a probable partial separation of the lead styphnate from the wire with a resulting decrease in reliability of initiation of the main charge. The completed bead is allowed to dry for approximately one minute before removing the wire from the clamp. This short drying period was found to give the bead sufficient strength to allow careful handling. The

complete detonators are then stored in a marked dessicator, containing active dessicant, until needed for preparing charges. The detonators were allowed to dry for at least 24 hours prior to using in charges to increase strength of the bead. Figure 4(G) shows a fully dried detonator as used in charges.

The above initiation system consisting of a high resistance wire through a lead styphnate bead which is completely covered by a coating of lead azide was arrived at by trial and error and was accepted as giving excellent results, nearly 100%, when detonators and charges were properly prepared and had no obvious defects. Several other initiation trains were tried. It was found that lead styphnate alone would not initiate detonation in the P.E.T.N. charges even though beads of size equal to or greater than the accepted detonators were tried. The use of lead azide alone was tried but was not successful. Lead azide being relatively insensitive to heat, the firing circuit used would not cause detonation of pure lead azide. Since the firing circuit would detonate the heat sensitive lead styphnate, a mixture of one part lead styphnate thoroughly mixed with two parts of lead azide was tried. The firing circuit would cause detonation of this mixture, but in each of four cases tried this type detonator failed to initiate detonation in the P.E.T.N. charges.

The following description of the technique used in actually pressing the charge is intentionally fairly detailed. This procedure developed from a good deal of trial and error and is given here to help others who desire to continue this or other projects requiring such charges. It was found necessary to make several modifications to the die after the initial design before acceptable results were obtained. A sketch of

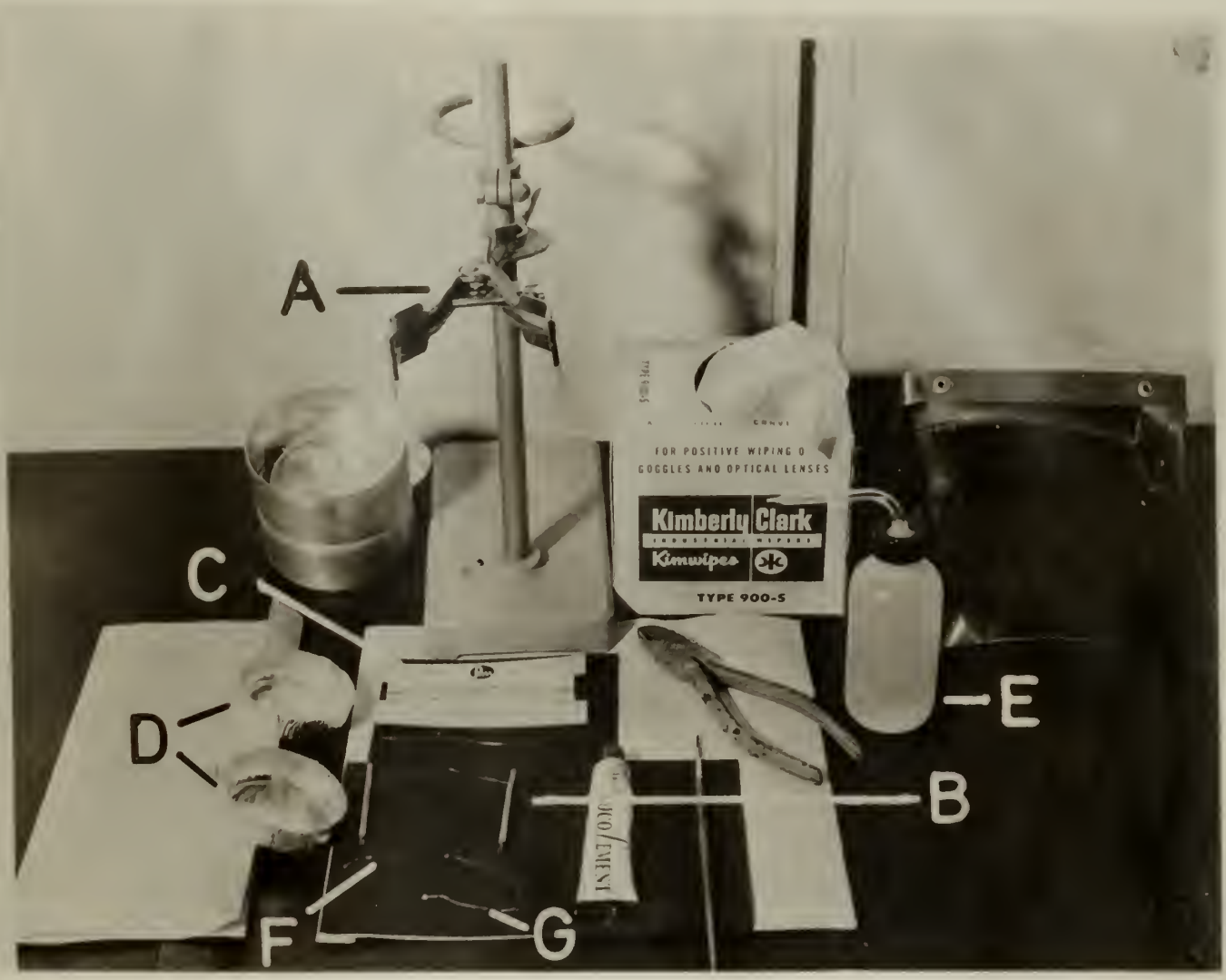


Fig. 4

A - Laboratory Clamp
B - Match Stick+Wire
C - Fuse Wire
D - Aluminum Cup
E - Acetone Bottle
F - Styphnate Bead
G - Complete Detonator

the die in final form is included as Figure 6. Using this die and the procedure below, a high percentage of spherical charges of 0.3 gram P.E.T.N. were obtained without significant difficulty. An effort will be made to give the reason for most of the steps.

Figure 5 shows the implements necessary to produce spherical charges. The P.E.T.N. is accurately weighed on an analytical balance to 0.3 gram and placed on the watch glass (A). The die base (B), die body (C), and plunger (D) are first cleaned with acetone from the plastic bottle. Visual inspection is necessary to make sure the small brass plunger in the die body is flush with the hemispherical cavity and that the allen set screw in the bottom of the die base is against this plunger. The steel block (E) is a convenient place to set the plunger (D) in an upright position until it is needed and also may be used to press the charge in a hydraulic press, if desired.

The die body is assembled to the die base making sure that the "O" on the die body is on the same side as the "O" on the die base. This insures the best fit each time for these two parts. The glass funnel is inserted into the die body and approximately 1/3 of the measured 0.3 gram charge is pushed into the funnel and the funnel tapped lightly to settle the explosive into the die. CAUTION: A face mask should be worn during all operations involving the explosive and detonators. The funnel is removed and the brass plunger (F) inserted into the die body, allowing it to exert the force of its weight on the P.E.T.N. in the die. The purpose of this plunger is to very lightly compress the partial charge into a hemisphere before inserting the detonator so that the detonator will finally rest near the center of the finished charge rather than being pushed off center during the pressing operation.

After the plunger is removed, any small particles of P.E.T.N. stuck to the bottom are tapped back on to the watch glass with the remainder of the charge. The die body is removed from the die base so that the detonator may be installed. The ends of the detonator wire are placed through the two holes in the bottom of the die base and the detonator pellet is centered above the hemisphere of P.E.T.N. The ends of the wire must be pulled tight so that the wire lies in the grooves in the die base before the die body can be fully reseated. When the detonator is in place and the wire has been worked into the grooves, the die body is carefully replaced, making sure that the "O's" are aligned and that the die body seats all the way. Most of the time when the die body does not seat properly it can be remedied by pulling on the exposed ends of the detonator wire with tweezers or needle-nosed pliers; otherwise, the die body must be removed and the wires replaced in the grooves. After the die body is again in place, the glass funnel is reinserted and the remainder of the charge tapped into the die. The funnel is removed and the plunger inserted into the die body. Some force is required since the sharp edges of the plunger bottom tend to be belled out during the pressing operation. The stop collar (G) is placed under the enlarged portion of the plunger. This collar prevents the possibility of ruining the plunger by pressing too far, and affords a consistent charge pressure and size. The assembled die is placed in the press. The die must be positioned under the rotating screw so that the pressure is straight down. Failure to do this will cause charge breakage when pressure is released. In the interest of safety the actual pressing is done from the other side of the laboratory bench. The raised center of the bench affords ample protection. In other locations suitable safety precautions

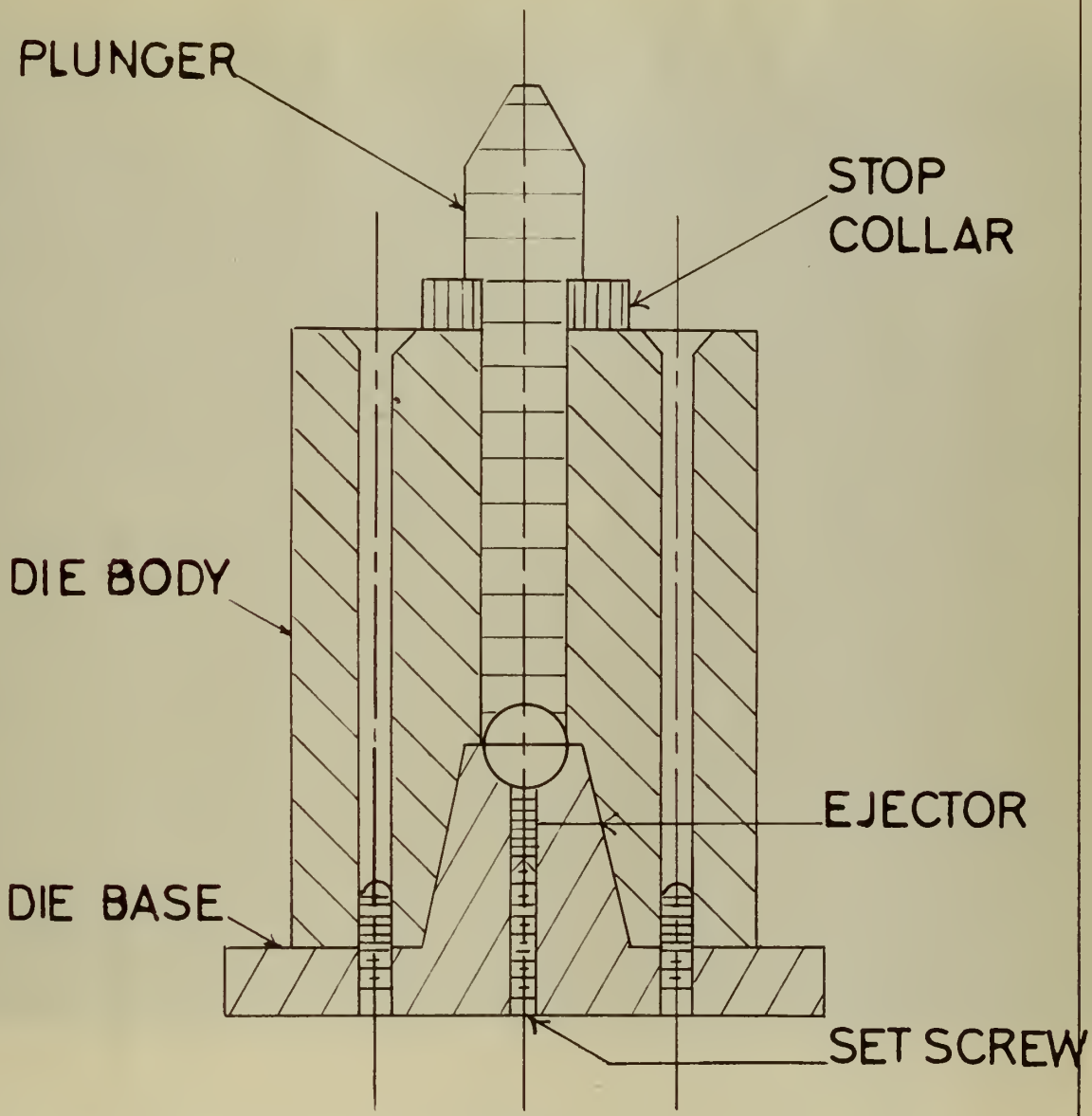
should be employed. The press is rotated with the small pipe extension until the stop collar is barely movable with the fingers. The stop collar is removed without releasing pressure on the die plunger. An attempt is made to raise the die body around the plunger with the fingers. This will separate the die body from the small rim on the equator of the charge without breaking the charge since it is still compressed. If it is not possible to raise the die body easily, the puller (H) is placed in position so that the square bottom plates fit into the milled slots in the side of the die body and the conical tip of the large set screw is in the indention in top of the press handle. By turning this set screw the die body will be raised away from the die base. The die body is allowed to return and rechecked to insure proper seating. The puller, if used, is removed. The press handle is turned slowly to release pressure on the die plunger. The entire die is removed from the press while holding the die body and die base together with a firm pressure. The die is placed on the edge of the workbench and the plunger gently raised with a slight twisting motion. The die body is then raised straight up from the die base exposing the charge imbedded in the die base. Tweezers are used to pull the detonator wire back through the holes in the die base and any excess P.E.T.N. is cleaned away from the equator of the charge. To remove the charge from the die base a small allen wrench is inserted in the set screw in the bottom of the die base and turned clockwise approximately 1/4 of a turn. This will loosen the charge so that it may be easily removed by the detonator wire. The charges are stored in a dessicator with fresh dessicant until needed.

Charges produced as above are reasonably spherical and detonation is from very near the center. A small amount of P.E.T.N. is unavoidably

lost during the pressing operation, but accurate measurement of the initial amount and care in all operations produced charges which weighed 0.3 gram complete with less than plus or minus 0.025 gram variation. Press density was approximately 1.6 gm/cm^3. A complete charge and a half charge showing location of the detonator are shown in Figure 7. The diameter of the completed charge is 0.278 inches.

Fig. 5

A - Watch Glass
B - Die Base
C - Die Body
D - Plunger
E - Steel Block
F - Brass Plunger
G - Stop Collar
H - Puller



DIE FOR PRESSING SPHERICAL CHARGE

Fig 6

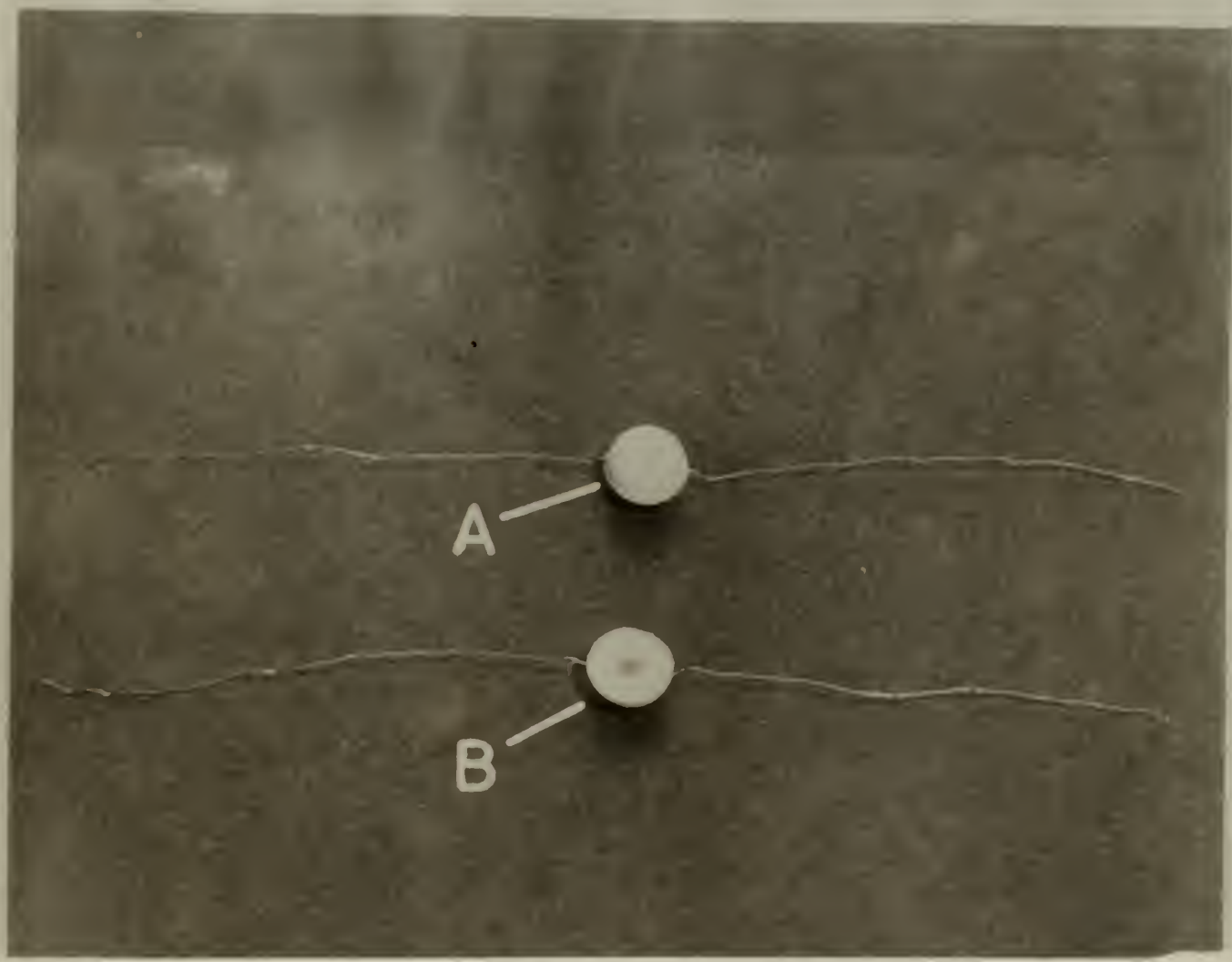


Fig. 7
A - Complete Charge
B - Charge Cross Section

4. Experimental Procedure

This experiment consisted of obtaining a series of photographs of spherical shock waves at 20 microsecond intervals over a range of 600 microseconds.

For each test shot fired in this series the prevailing ambient conditions of atmospheric pressure and relative humidity were read and recorded. Since this work was performed in a laboratory with thermostatic temperature control the variation of temperature throughout the investigation was negligible.

In setting the delay time for each test shot the following procedure was used. Using the method described previously under the calibration of the electronic delay the strobotac unit was used to set, as accurately as equipment permitted, the total delay time desired for that particular shot. Prior to firing the undelayed output from delay unit Number one was connected to trigger the sweep of the oscilloscope. The delayed output would then be presented as a pip on the trace. As the shot was fired this trace was photographed by a polaroid camera mounted on the oscilloscope. The time shown by this trace of course did not include the delay encountered in the photocell unit. But by reading this time and entering the calibration curve with this figure the total delay time could be obtained.

As an additional precaution, immediately after completion of each shot the strobotac was again set up and the true total delay was checked and recorded.

These three total delay times were then compared. The comparison shows a maximum deviation from the desired time of three microseconds. These large deviations occurred in the very short delay time where there

seemed to be some instability in the delay unit. In the range of time from 100 microseconds to 600 microseconds the maximum deviation was two microseconds, which is also about the limit of visual accuracy in reading the settings through most of this range.

It is believed that the timing as done in this experiment can be accepted as accurate to within two percent.

To obtain shock radii positive prints were made from the exposed negatives. A traveling comparator microscope was utilized to read the radii from these prints. The procedure used depended upon the charge being accurately placed so that in the photograph the center of the detonation appeared at the intersection of two of the ten centimeter grid lines on the screen. This was accomplished by constructing a jig which placed the charge in the same position, relative to blast table and screen, for each shot. By using this jig the charge was, for each shot, placed precisely 66.74 cm from the screen, 50.4 cm below the blast table, and 51 cm above the laboratory bench. These heights place the charge on the same level as the light. Alignment on the camera to screen line, with the vertical grid line on the screen, was accomplished by placing the feet of the alignment jig in marked positions on the laboratory bench.

This mechanical positioning was visually checked using a black disk with a white center positioned on the screen so that when viewed through the camera the suspended charge, if properly positioned, appeared to coincide exactly with the white center.

In reading the radii from the photographs the following procedure was followed. The number of ten centimeter squares from the explosion center to the square containing the shock shadow were recorded. Using the comparator microscope, readings were taken for the distance from the

grid line nearest the explosion center to the shock wave shadow and for the entire distance across that particular grid square containing the shock shadow. These numbers then provided a ratio which when multiplied by ten and added to ten times the number of squares intervening between this square and the explosion center gave the radius of the shadow of the shock wave as cast on the screen.

It was then necessary to reduce the radii as read from the photograph by an appropriate factor to obtain true shock size at the plane of the charge. The measured distance from the screen to the camera lens was 333.7 cm. The above screen to charge and screen to camera distances provided a factor of 1.25 for easy mathematical computation and compatibility with the space available for this experiment.

With the total radius of the shock shadow on the screen, it was necessary only to divide by 1.25 in order to have the radius of the shock wave at the plane of the charge.

This procedure was followed to obtain four radii for each shock wave photographed, each radius lying on one of the grid lines leading out from the apparent center of the explosion as it appeared on the photograph. The average of these four radii was then taken as the true radius of the shock wave for this particular time delay.

Using these procedures it is felt that the measurement of shock radii is accurate to within plus or minus one millimeter. Figures 8 and 9 show representative photographs from this series. The visibility of portions of the shock wave has been lost during photographic reproduction.

A further series was run as a preliminary investigation into the use of this method in the study of reflected shock waves from a heated plate and from a plate at ambient temperature. Although the method

proved entirely feasible, lack of time prevented the obtention of sufficient quantitative results. A survey of this investigation is included for interest as Appendix III.

5. Data

Basic data obtained from the above experimental procedure is included as Table 1. This data includes radii of the second or inner shock (R_i) from the point at which it is first visible on the photographs.

TABLE 1

t(μ sec)	R_o(cm)	R_i(cm)	P_o(mm Hg)	R.H.(%)
20	8.24		768.0	45.0
40	9.92		768.6	45.0
60	11.60		768.6	45.0
80	13.15		768.6	45.0
100	14.64		767.8	45.0
120	15.10		767.4	45.0
140	15.98		766.2	23.5
160	17.78		766.2	23.5
180	18.02	8.69	766.2	23.5
200	19.14	10.41	766.2	24.0
220	20.24	11.45	766.1	22.5
240	21.48	13.00	766.1	22.5
260	23.00	13.66	766.1	23.0
280	23.17	13.82	766.6	44.5
300	24.03	14.45	766.5	43.0
320	24.77	15.30	766.5	45.0
340	25.75	15.90	766.5	45.0
360	26.56	17.19	766.5	46.0
380	27.56	17.97	766.5	45.5

Table 1 (Continued)

t(μ sec)	R_o(cm)	R_i(cm)	P_o(mm Hg)	R.H.(%)
400	28.18	18.54	768.0	44.0
420	29.86	20.02	768.0	44.5
440	30.67	20.40	768.0	45.0
460	30.95	21.23	768.0	45.0
480	32.05	21.95	766.2	42.0
500	32.58	22.02	765.9	42.0
520	33.80	23.02	768.4	44.0
540	34.67	23.84	772.5	41.0
560	35.74	24.60	772.6	39.5
580	36.39	25.23	772.6	39.5
600	37.07	25.98	772.6	38.0

6. Computational Procedure

The following computations were made in order to arrive at a comparison of this experiment with results listed in Reference 1.

P_o as recorded in original data is in millimeters of Mercury. It was necessary to convert this to units of dynes/cm^2. Since this experiment was conducted in a laboratory equipped with thermostatic temperature control, a temperature of 20^o C. was accepted as prevailing ambient temperature throughout the experiment. At 20^o C. the density of Mercury is listed as 13.55 gms/cm^3. This yields a conversion factor of 1328.4 dyne/cm^2 = 1 mm Hg at 20^o C. Then $P_o = (1328.4)(P)$ where P is observed pressure in mm Hg.

Pressures in dynes/cm^2 were calculated for each observed pressure. These were found to range from a high of 1.0263 dyne/cm^2 to a low of 1.0174 dyne/cm^2. Then to within the limits of accuracy of this experiment the pressure P_o could be taken as a constant 1.02 dynes/cm^2.

In the computation of overpressure from arrival time data, it is convenient to introduce the mach number and a time interval, t_a, which is the time required for a sound wave to travel the same distance under prevailing ambient conditions.

By definition

$$t_a = (1/a) \int_o^R dR$$

and

$$t = (1/a) \int_o^R 1/M \; dR$$

Combining these equations leads to

$$t_a - t = (1/a) \int_o^R (1-1/M) \; dR$$

or

$$(1/a)(1-1/M) = d(t_a-t)/dR$$

Solving for M

$$M = \frac{1}{1 - a\left[\frac{d(t_a-t)}{dR}\right]}$$

where $\left[\frac{d(t_a-t)}{dR}\right]$ is the slope of the curve obtained by preparing a graph of differences in arrival time of a sound wave and the actual shock wave (t_a-t) versus the observed distance (R).

Speed of sound under prevailing ambient conditions was calculated by

$$a = (\gamma P_o/\rho)^{\frac{1}{2}}$$

where γ (the ratio of specific heats c_p/c_v) is taken as 1.403.

Since the relative humidity throughout this experiment, with few exceptions, was 40% or over, the density was taken as the density of moist air at 20° C. A value of .001217 gm/cm^2 was used.

Speed of sound (a) was then calculated for each ambient condition observed during the experiment. The values were found to range from a high of 34396 cm/sec to a low of 34248 cm/sec. A value of 34300 cm/sec was accepted as being within the limits of accuracy of this experiment.

Using this value, time of arrival of a sound wave at any observed radius was calculated by

$$t_a = \frac{R}{34300} \times 10^6$$

where t_a is in microseconds (sec x 10^{-6}).

With the Mach number (M) calculated for each observed shock radius from the above information the overpressure (ΔP) exerted at that point was taken from Table 1 of Reference 3.

In order to make possible the direct comparison of different explosives, it was found convenient to adopt the parameters used in Reference 1. One of these parameters is a reduced energy parameter involving the total energy release of the explosion. To calculate this total energy release a method, derived by Gilbert F. Kinney, Professor of Chemical Engineering, U. S. Naval Postgraduate School, was utilized. Calculations using this method are included as Appendix II. These calculations yield a value of 7.69×10^{10} ergs total energy release for each gram of P.E.T.N. exploded.

In calculating charge weight average values of several weighed quantities were used. These are listed as follows:

.3244 gms - average complete charge weight.

.0303 gms - average complete detonator weight.

.0213 gms - average weight of wire plus Lead styphnate bead.

.0179 gms - average weight of detonator wire.

From these data:

The average weight of Lead styphnate used was .0034 gms. By Trauzel test Lead styphnate is rated at 40% the strength of TNT so .0034 gms Lead styphnate = .0014 gm equivalent TNT.

The average weight of Lead azide used was .0090 gms. By Trauzel test Lead azide is rated at 39% the strength of TNT so .0090 gms Lead azide = .0035 gms TNT equivalent.

By Trauzel test P.E.T.N. is rated as 173% the strength of TNT. Then summing the TNT equivalents for Lead azide and Lead styphnate .0069 gms TNT equivalent = .0040 gms equivalent P.E.T.N.

The average weight of P.E.T.N. in each charge was, from above data, .29410 gms + .0040 gms P.E.T.N. equivalent = .2981 gms.

Within the limits of error of this experiment the charge weight could be taken as 0.3 gms P.E.T.N.

The total energy release for each charge (Δ A) was then calculated to be $(7.69 \times 10^{10})(0.3) = 2.307 \times 10^{10}$ ergs.

The parameter α was then calculated using $\alpha = (\Delta A/P_o)^{\frac{1}{3}}$ for each ambient condition observed during the experiment. These calculations yielded a high value of 28.207 cm and a low value of 28.125 cm with a mean of 28.20. This mean value was accepted as being within the limit of error for this experiment.

From this the dimensionless parameter λ was developed, by $\lambda = R/\alpha$, for each observed radius of shock wave.

The dimensionless parameter τ was developed from the formula $\tau = ta/\alpha$ where t = time of arrival of the shock wave at a specified observed radius (in sec).

a = speed of sound under prevailing ambient conditions (in cm/sec).

$\alpha = (\Delta A/P_o)^{\frac{1}{3}}$ as developed above.

The data taken from Reference 2 were reduced to the proper parameters by similar calculations. The amount of explosive was assumed as one pound of 50/50 pentalite. The value of 7.69×10^{10} ergs/gm from above was used for the energy release of P.E.T.N. and a similarly calculated value of 4.814×10^{10} ergs/gm was used for the energy release of TNT. These figures yielded a total energy release for one pound of 50/50 pentalite of 28.36×10^{12} ergs. Ambient pressure, P_o, was again taken as 1.02 dynes/cm^2 and further reduction to the necessary parameters was done as illustrated above. Δ P was obtained by dividing the pressures given in this work by 14.7 psi.

7. Results

As is evident by the shock wave photographs included on Figures 8 and 9 and also on all other photographs taken, the charges used produced very symmetrical shock waves. Of significance is the fact that these photographs do show the existence of a second or inner shock following the primary shock wave from this small spherical charge detonated from the center.

The scaled distance ($R/W^{\frac{1}{3}}$) versus scaled arrival time ($t/W^{\frac{1}{3}}$) is shown in Figure 10. The data as presented in this manner show a reasonably smooth growth of the primary and secondary shock radii with fairly small dispersion of the experimental points. The scaling used permits comparison of this data with P.E.T.N. charges of different weight.

Peak overpressure as a function of shock radius is shown as Figure 11. Also presented are the data from Figure 1 of Reference 1. These data represent the numerical solution of the partial differential equations of hydrodynamic motion, for the case of a center-detonated spherical charge of TNT, as accomplished on a high speed computer. Also shown are corresponding data as calculated from the data presented in Appendix III of Reference 2. These data were obtained through the measurement of air blast peak pressures from bare spherical charges of 50/50 pentolite ranging from one-half to eight pounds.

The parameters used in presenting these data, through the reduced energy factor, allow the comparison of different sizes of charges made from different types of explosives. While the agreement is not exact, there would seem to be a reasonable correlation between these three methods of investigation.

The position of the primary and secondary shocks as a function of

time is shown in Figure 12. Reduced parameters again are used for comparison with data from Figure 4, Reference 1. Here the agreement of data for the primary shock is good; however, the agreement between the observed secondary shock wave and the secondary shock as predicted by Brode in Reference 1 is not what would be expected after the better correlation of primary shocks. Brode predicts that the secondary shock follows a rarefaction wave into the gaseous products. He states, "It starts with zero strength and grows as it moves inward through these gases. It is swept outward in space until the expansion of the high explosive products is nearly exhausted, then it implodes on the origin and is reflected outward to the contact surface. At the time that it strikes the contact surface between the TNT gases and the air, the TNT gases are still more dense and much cooler than the air immediately outside, (this is generally true at any time). As a consequence, the shock in passing through the surface sets up an inward rarefaction wave. This rarefaction, like the second, implodes on the origin, reflects and moves out in the wake of the previous shocks. The succession of shocks continues in this fashion until the energy in the explosive product gases is dissipated." By Brode's predictions we should have been able to observe a third shock at 540 microseconds with a radius of 9.04 cm. This shock is not visible on any results up to and including 600 microseconds. This may be a result of the relative weakness of this shock as predicted by Brode.

Application of the 1/3 scaling laws in order to use experimental results from larger charges yields a value of approximately 63 microseconds for the duration of the positive phase from these small charges. Considering the fact that the negative phase is usually of longer duration

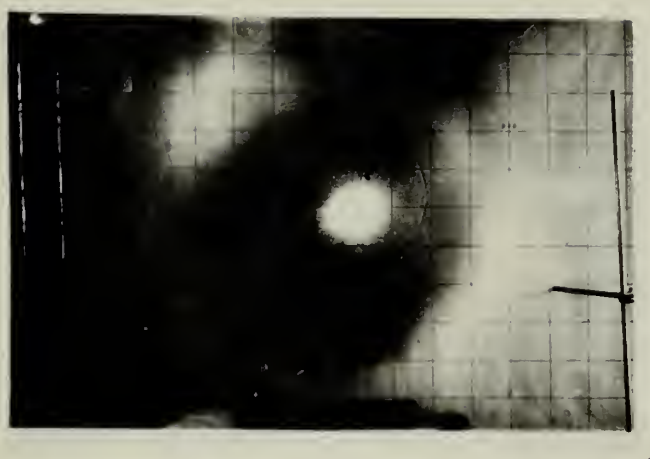
than the positive phase the observed distance-time relation of 8.69 cm at 180 microseconds is acceptable under the gas bubble pulsation theory as applied to air.

There are many complicating factors in the second shock wave phenomenon and further investigation will be required to provide solution.

The most significant result of this investigation is that it appears entirely feasible to conduct investigation of explosive shock phenomena by this method. Improvement in equipment and technique would undoubtedly lead to more exact results. It should be possible to incorporate additional equipment such as multiple light flash, pressure gauges, and ionization probes to further the usefulness of the method. The use of accurate pressure gauges would provide a check on this method of computing overpressures from essentially velocity information. Using this method it would be possible to study shock wave profiles from different sizes, shapes and types of explosives. Also, it would be possible to use this method as a means of determining the relative strength of different explosives. Of special interest would be a continuation of the reflection study mentioned in Appendix III.

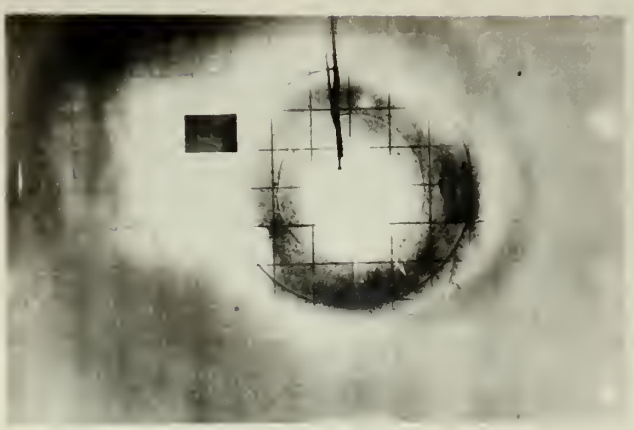
The advantages of this method are manifold. The results obtained in this investigation appear to correlate reasonably well with results obtained from larger amounts of explosive with more extensive instrumentation. By the use of these very small charges the space required is greatly reduced and experiments of this nature become feasible in the controlled atmosphere of a laboratory. Reduction in the size of the charges alleviates, to some extent, the danger inherent in conducting experiments of this nature. With the basic equipment procured many different experiments may be conducted with the cost limited to expenditure

for explosive material and photographic supplies. Finally, the method provides a simple compact means of obtaining visual evaluation of shock phenomena.



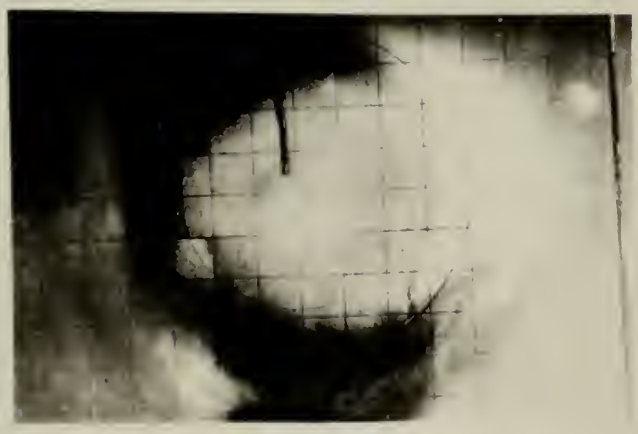
TEST SHOT 7
120 usec
R 15.10 cm

TEST SHOT 12
200 usec
R_o 19.14 cm
R_i 10.41 cm



TEST SHOT 24
320 usec
R_o 24.77 cm
R_i 15.30 cm

TEST SHOT 28
400 usec
R_o 28.18cm
R_i 18.54cm



TEST SHOT 34
480 usec
R_o 32.05cm
R_i 21.95cm

TEST SHOT 34
Timing Picture
50 usec/cm

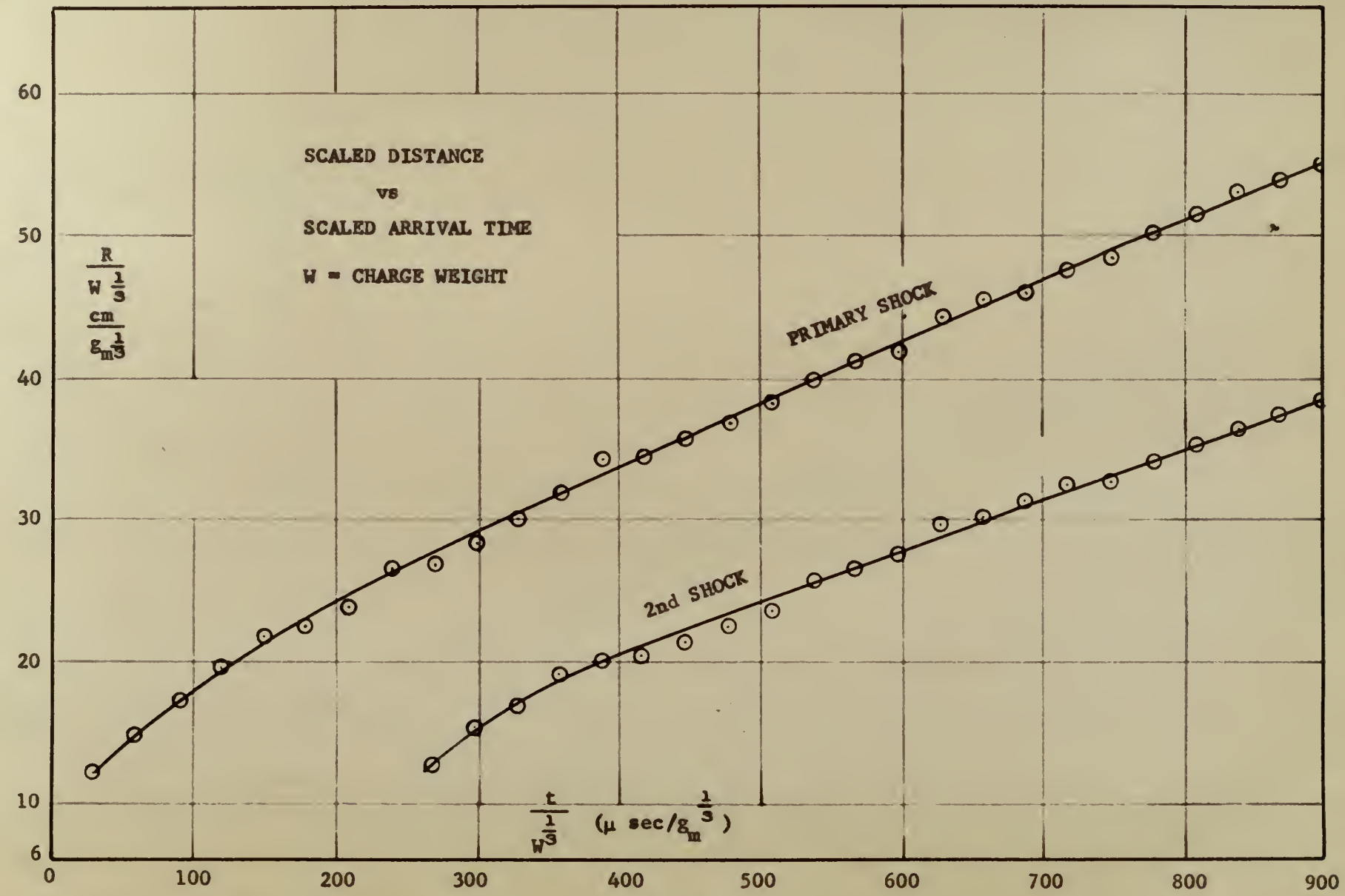

SCALED DISTANCE
vs
SCALED ARRIVAL TIME
W = CHARGE WEIGHT
R / W^1/3 cm / g_m^1/3
PRIMARY SHOCK
2nd SHOCK
t / W^1/3 (μ sec/g_m^1/3)
60
50
40
30
20
10
6
0
100
200
300
400
500
600
700
800
900

Fig 10

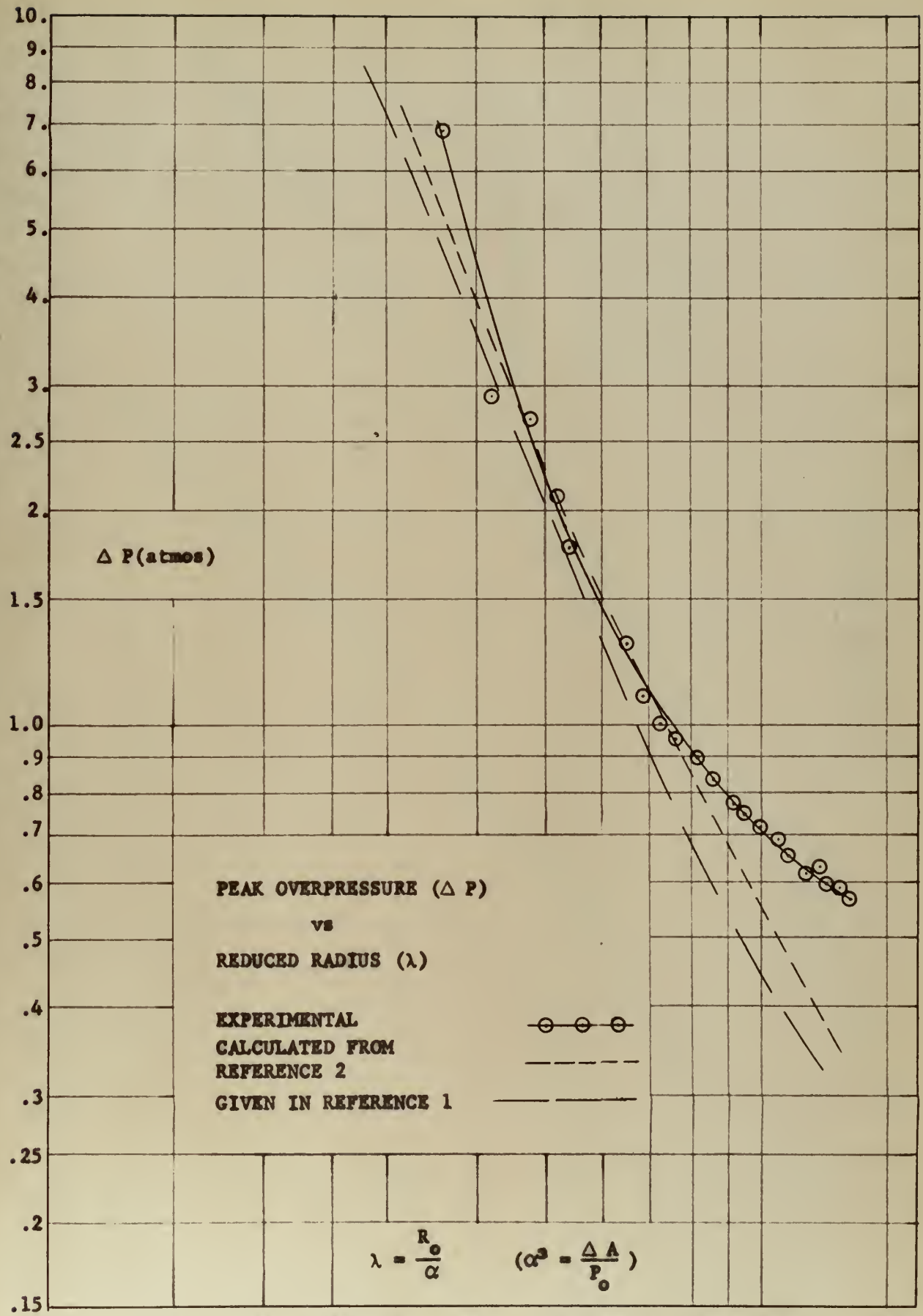

10.
9.
8.
7.
6.
5.
4.
3.
2.5
2.
1.5
1.0
.9
.8
.7
.6
.5
.4
.3
.25
.2
.15
Δ P(atmos)
PEAK OVERPRESSURE (Δ P)
VS
REDUCED RADIUS (λ)
EXPERIMENTAL
CALCULATED FROM
REFERENCE 2
GIVEN IN REFERENCE 1
$\lambda = \frac{R_o}{\alpha}$ $(\alpha^3 = \frac{\Delta A}{P_o})$
.1
.15
.2
.25
.3
.4
.5
.6
.7
.8
.9
1.0
1.5

Fig 11

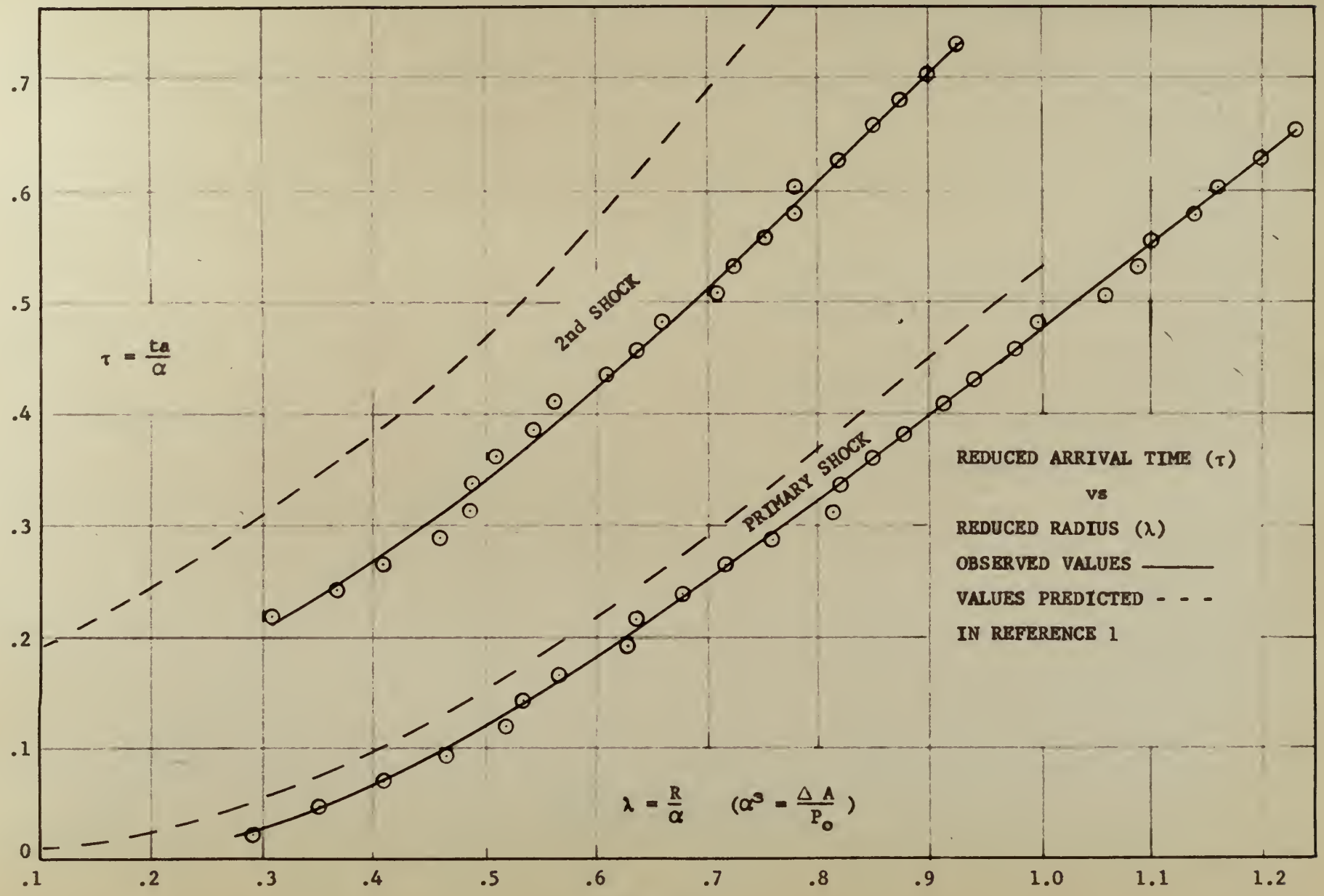
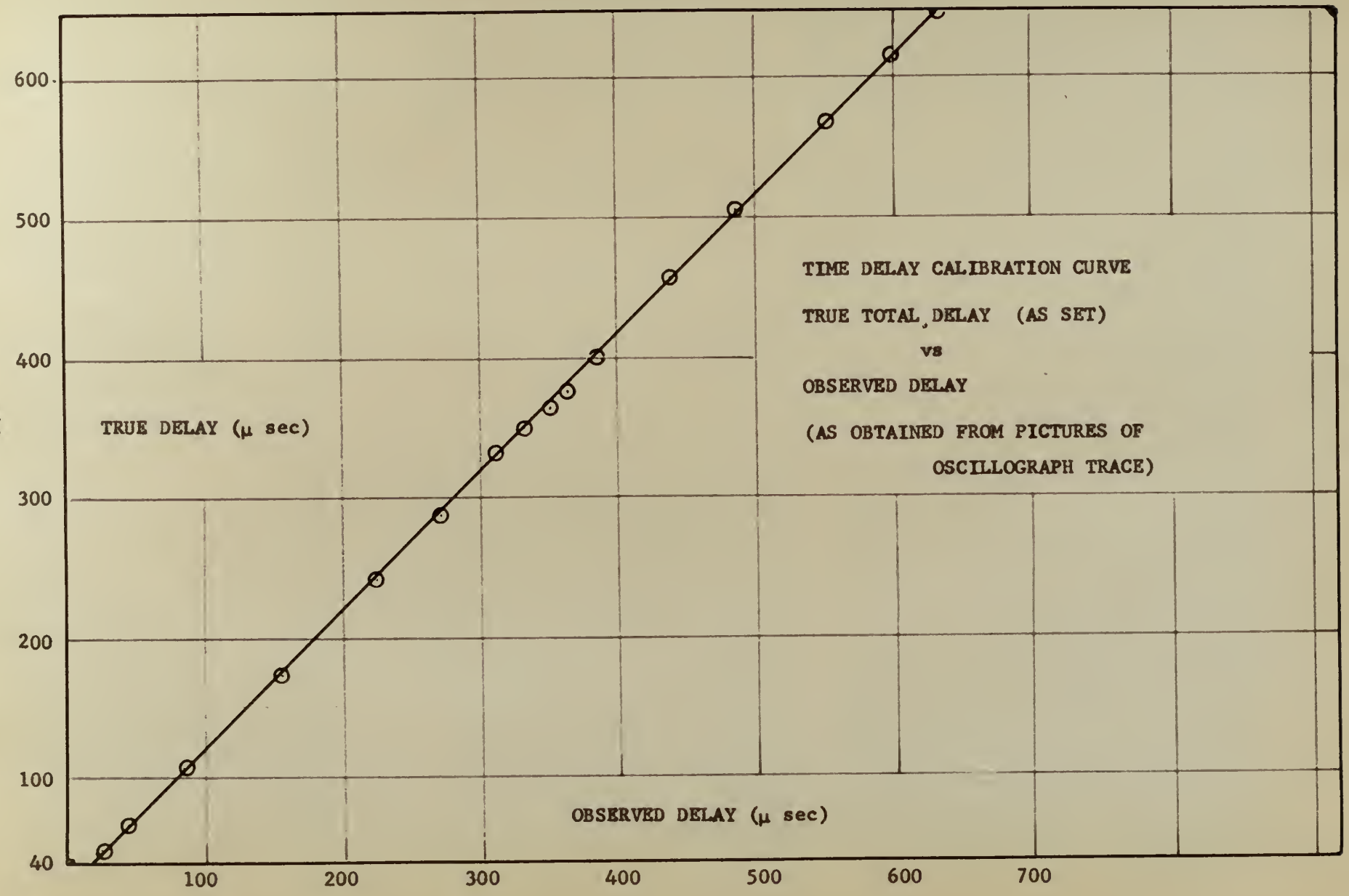

.7
.6
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
$\tau = \frac{ta}{\alpha}$
2nd SHOCK
PRIMARY SHOCK
REDUCED ARRIVAL TIME (τ)
vs
REDUCED RADIUS (λ)
OBSERVED VALUES ———
VALUES PREDICTED - - -
IN REFERENCE 1
$\lambda = \frac{R}{\alpha}$ $(\alpha^3 = \frac{\Delta A}{P_o})$

Fig 12


TIME DELAY CALIBRATION CURVE
TRUE TOTAL DELAY (AS SET)
vs
OBSERVED DELAY
(AS OBTAINED FROM PICTURES OF OSCILLOGRAPH TRACE)
TRUE DELAY (μ sec)
OBSERVED DELAY (μ sec)
600
500
400
300
200
100
40
100
200
300
400
500
600
700

APPENDIX II

The Energy of Explosion (ΔA) was calculated by $\Delta A = \Delta E - T \Delta S$ where ΔE is the Heat of Explosion, corresponding to an internal energy decrease, and ΔS is the entropy growth for the process. In calculating these quantities it is necessary to make several assumptions, one of which is that the process is isothermal. While this is of course not a true condition, it is a good first approximation and yields reasonable results. A second assumption is the formation of the explosion products. In this case a set of "nominal" products are assumed and calculations are based on these nominal products. This again is a reasonable first approximation and yields good results.

ΔE then is calculated as the difference of the energy of formation of the explosive and the energy of formation of the "nominal" explosion products. Reference 4 lists the heat of formation for P.E.T.N. as 383 cal/gm. This value was accepted for use in these calculations.

The "nominal" products of explosion are obtained by distributing oxygen available in the explosive formula first to formation of CO, second to formation of H_2O, third to formation of CO_2, and finally to free oxygen. Then for P.E.T.N. the "nominal" reaction is

$$C_5H_8N_4O_{12} \rightarrow 3CO_2 + 2CO + 4H_2O(g) + 2N_2$$

The energies of formation of these "nominal" products were taken from notes of Professor G. F. Kinney as follows:

CO_2 : -94.05 Kcal/gm mole

CO : -26.72 Kcal/gm mole

$H_2O_{(g)}$: -57.50 Kcal/gm mole

Then

$$\Delta E = E_2 - E_1$$

$$= 3(-94.05) + 2(-26.72) + 4(-57.50) - (-383)(316)$$

$$= -565.61 + 121.03$$

$$= -444.58 \text{ Kcal/gm mole.}$$

The entropy of explosion (ΔS) was calculated by $S = S_p - S_o$ where S_o is the entropy of the explosive and S_p is the entropy of the "nominal" products plus the "entropy of mixing" for the gaseous products.

S_o, the entropy of the explosive, was approximated by the formula $S_o = 15 + 3.3n$ where n is the number of atoms, exclusive of hydrogen, contained in the molecular formula of the explosive. For P.E.T.N.

$$S_o = 15 + 3.3(21) = 84.3 \text{ cal/gm mole } ^oK$$

S_p, the entropy of the "nominal" products was calculated by

$$S_p = S_{CO_2} + S_{CO} + S_{H_2O} + S_{N_2}$$

where

$$S_{CO_2} = S^o_{CO_2} + 1.986 \ln \frac{N'}{N} N$$

in which N' = the total number of moles of gaseous products formed.

N = the number of moles of gaseous CO_2 formed.

$S^o_{CO_2}$ is the absolute entropy of CO_2.

The absolute entropies of the "nominal" products were taken as follows:

CO_2 : 51.06 cal/gm mole ^oK

CO : 47.03 cal/gm mole ^oK

$H_2O_{(g)}$: 45.11 cal/gm mole ^oK

N_2 : 45.77 cal/gm mole ^oK

The value 1.986 ln N'/N is added to the absolute entropy in this case to account for the "entropy of mixing" of the gaseous products.

From these data:

$$S_{CO_2} = 3(51.06 + 1.986 \ln 11/3)$$
$$= 160.93 \text{ cal/gm mole } ^oK$$

$$S_{CO} = 2(47.30 + 1.986 \ln 11/2)$$
$$= 101.37 \text{ cal/gm mole } ^oK$$

$$S_{H_2O} = 4(45.11 + 1.986 \ln 11/4)$$
$$= 188.46 \text{ cal/gm mole } ^oK$$

$$S_{N_2} = 2(45.77 + 1.986 \ln 11/2)$$
$$= 98.31 \text{ cal/gm mole } ^oK$$

Then

$$\Delta S = 160.93 + 101.37 + 188.46 + 98.31 - 84.3$$
$$= 464.77 \text{ cal/gm mole } ^oK$$

Then using

$$\Delta A = \Delta E - T\Delta S$$

$$\Delta A = -444.58 - 293(464.77)/1000$$
$$= -580.84 \text{ Kcal/gm mole}$$

Converting to ergs:

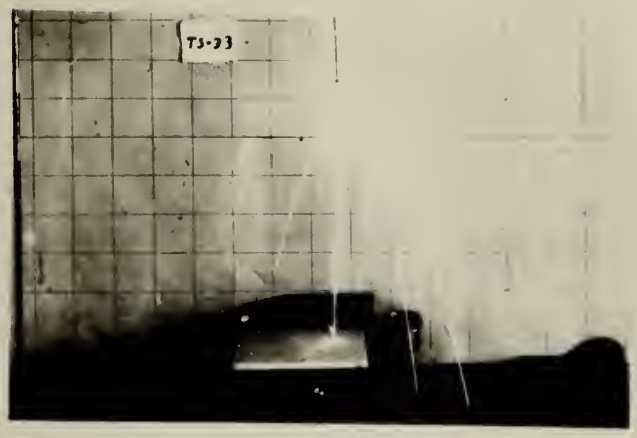
$$1 \text{ Kcal} = 4.186 \times 10^{10} \text{ ergs}$$

$$\Delta A = -580.84/316 \ (4.186 \times 10^{10})$$
$$= 7.69 \times 10^{10} \text{ ergs/gram.}$$

APPENDIX III

Shown in Figure 13 are two of the results obtained during an experimental investigation of the feasibility of using this method to study the ideal and non-ideal reflection of a spherical shock wave. In order to obtain photographs of the reflected shock the blast table was lowered to the level of the camera lens. No difficulty was encountered in obtaining photographs of the normal reflection with formation of the Mach Stem. However, it was expected that the formation of a thermal layer by heating the plate would cause the leading edge of the Mach Stem to advance in the region of the thermal layer. This expected result was not obtained with the equipment available. It is believed that the thermal layer was not at a high enough temperature and was perhaps too thick. The highest temperature obtained at the plate was 175° C. This was by using eight laboratory hot plates. Adequate heating circuit for the plate could easily extend this temperature. Lack of time prevented continuation of this experiment, but it is felt that the necessary heating could be accomplished and the expected results obtained.

The low order detonation shown as Test Shot 33 on Figure 13 is of interest in comparison with a normal detonation.



TEST SHOT 33
Low Order

TEST SHOT 56
300 usec
Plate Temp 156°C

TEST SHOT 58
200 usec
Plate Temp 170°C

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